TASK MODELS TO GUIDE ANALYSIS: USE OF THE OPERATOR FUNCTION MODEL TO REPRESENT MODE TRANSITIONS

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The paper demonstrates the use of a task-analysis model to represent mode transitions in a modern "glass cockpit" jetliner. The operator function model (OFM), employed for this analysis, is a normative and nondeterministic model of how a well-trained crew may decompose control functions into simpler activities, and coordinate those activities to meet system goals. Using a portion of a complete OFM model, we trace three examples of mode transition; these examples were collected during a recent field study of mode usage onboard Boeing B-757 aircraft. Three examples are analyzed and several mode usage problems are highlighted. Finally, we discuss some of the limitations and advantages of task-analysis mo-dels for understanding human-automation interaction.

In the context of human-machine interaction in complex and dynamic systems, the introduction of automatic and semi-automatic control has led to the proliferation of modes. These modes are the methods by which the operator selects and engages specific system behavior. Since most complex systems are made up of several components (e.g., pitch, thrust, roll)¾each with its own set of modes, the mode status of a multi-component system can be described as a vector. Each element in this vector contains the active mode of the corresponding component.

The operator, in this case a pilot, manually transitions among the various mode combinations depending on the situation, ATC clearance, procedures, and pilot technique (Degani, Shafto, and Kirlik, in press). Similarly, the control system itself triggers automatic transitions among various mode combinations depending on the conditions embedded in its software (Lambergts, 1983). An automatic control system, such as the automatic flight control system (AFCS) of a Boeing B-757 aircraft, exhibits numerous mode combinations¾some more automatic and some less. By engaging a given mode-combination the pilot specifies a given level of automation. This specification carries several implications: setup time, accuracy of flight path, fuel efficiency, and monitoring demands.

Specification of the 'proper' level of automation and its implications on managing the flight is an issue of much discussion and concern in the commercial aviation community (*Aviation Week and Space Technology*, 1995). And indeed, airlines address this issue by designing specific training modules, by developing specific procedures, and by articulating a philosophy for using flight-deck automation (Degani and Wiener, 1994). Nevertheless, evidence from investigations and voluntary reports suggests that incomplete knowledge of mode behavior is increasingly becoming a significant contributor to incidents and accidents (*Aviation Week and Space Technology*, 1995; Eldredge, Dodd, and Mangold, 1991).

The objectives of this paper are threefold: (1) to demonstrate the use of a model-based task-analysis to describe mode transitions, (2) to highlight some potential difficulties in using modes, and (3) to initiate a discussion of the utility of such models for describing and analyzing human-automation interaction.

METHOD

The approach, taken in this paper, is to build a task-analytic model and use it to analyze three mode-transition examples. The modeling methodology employed is the operator function model (Mitchell, 1987). The three examples were observed and documented during a recent field study of mode transitions in the B-757 aircraft.

Operator Function Model (OFM)

This task-analysis model attempts to represent in graph form how an operator might decompose control functions into simpler activities and coordinate those activities in order to supervise a complex system. Activities, in the OFM representation, can be either physical (e.g., push a button) or cognitive (e.g., verify a setting). The OFM is based on discrete control modeling approach; it exploits two features of human-automation interaction in supervisory control systems: One, that most actions taken by operators are discrete as opposed to continuous. Two, that many of these actions are specified by a mandated procedure or a recommended technique.

An OFM of crew interaction with the Boeing B-757 automatic flight control system (AFCS) was constructed using a plausible set of tasks that a crew flying the aircraft would use. The portion modeled here describes mode transitions in the vertical aspect of the flight path¾the most vulnerable aspect to mode problems (Sarter and Woods, 1994). The data to build the OFM were obtained from observations of flight crews during the field study, standard operating procedures at the airline, techniques and rules of thumb that pilots are taught during ground school, and techniques taught during initial operating experience (IOE) training. The model formulated in this analysis is organized with seven levels: phase of flight, functions, subfunctions, tasks, mode selection, subtasks, and actions (see Figures 1 and 2).

Data Collection

Mode transition data were collected by an observer sitting in the cockpit's jumpseat. A total of 66 observation flights (about 200 hours) were conducted onboard B-757 aircraft. Using a standardized data-sheet, the observer documented both quantitative and qualitative data. The quantitative dataset contained variables such as time of event, type of pitch, roll, and thrust modes that were manually or automatically triggered, altitude, speed, ATC clearance, weather, and several other variables. (For preliminary analysis of the quantitative data see Degani et al., in press). The qualitative data included verbal accounts of the reasons for mode transitions, specific cases of observed mode usage problems, and comments from flight crews about operating a modal system. The two types of data were critical for this analysis¾their combination allowed us to describe these mode transition scenarios in detail. Thirty examples highlighting mode usage issues were recorded during the field study. Of these thirty examples, three were selected for this analysis.

EXAMPLE 1

In this example, the captain asserted his authority to have the aircraft be flown at a lower level of automation than was initiated by the first officer. The situation occurred during the descent phase of the flight into the Atlanta International Airport. The aircraft was flying level at 24,000 feet and the VNAV/LNAV pitch/roll mode combination was active. The weather was stormy (a front with thunderstorms and rain); many aircraft were vectored around the cells and some were instructed to circle in holding patterns. The crew received the following ATC clearance: "[fly] direct [to the] ROME [waypoint] and cross [the waypoint] DALLAS at 14,000 feet and [at a speed of] 250 knots." The first officer (pilot-flying) started to program the flight management computer (FMC) accordingly. At that point, the captain (pilot-not-flying) interrupted the first officer and instructed him to engage the Flight Level Change (FLCH) mode; the first officer complied.

OFM Representation

The initial mode vector was VNAV-PATH, SPEED, and LNAV for the pitch, thrust, and roll components of the AFCS. The ATC clearance required a modification to the aircraft trajectory (function: *Modify/Monitor Vertical Trajectory;* subfunction: *Modify Trajectory*) (see Figure 1). The first officer set the altitude to 14,000 feet (task: *Modify MCP Altitude Target-Value*), identified the active mode¾VNAV (task: *Identify/Engage Mode*), and proceeded to *Modify Target Values* (enter waypoints, transition altitude, and speed). While the first officer entered these target-values into the control and display unit (CDU), the captain told him to engage the FLCH mode (task: *Identify/Engage Mode*).

Discussion

The representation in Figure 1 suggests why the captain elected to use FLCH rather than VNAV mode: the number of subtasks required to set up VNAV is greater than FLCH. The difference in number of subtasks between the modes translates to differences in total execution time, attention, and cognitive load (Casner, 1995). Additional factors are the sequential constraint in entering data in order to configure VNAV and the probability of making data-entry errors.

Once the aircraft landed, we asked the captain why he elected to engage the FLCH mode. He explained that he preferred to use FLCH in this situation because it is simpler than VNAV. In subfunction *Monitor Flight Parameters and Modes* and VNAV active, the crew has to monitor the aircraft trajectory, mode trajectory, and computed path trajectory. Comparison between the two dynamics and the resulting relationship to the computed path appears to require much of the crew's attention (this issue is further discussed in Scenario 2).

Additionally, the captain commented on the extent to which pitch and thrust components interact in affecting the aircraft trajectory. Although FLCH controls both pitch and thrust components, this mode somewhat decouples this interaction. During descent the throttles are retarded to idle thrust, and only pitch commands are used to maintain the speed target-value. Hence the FLCH mode minimizes the interaction between thrust and pitch by fixing one variable (thrust) and varying the other (pitch). In contrast, the VNAV mode varies both pitch and thrust values when the aircraft deviates from the computed path (see Figure 2, Automatic Mode Engagements). Another related factor, not directly shown by the model, was also part of the captain's decision: in situations where he has to perform and monitor many other tasks (thunderstorm activity, other aircraft in the vicinity, party-line transmissions), he was willing to sacrifice precision and fuel efficiency for simplicity in monitoring the AFCS.

EXAMPLE 2

In this example, the crew was not completely aware of the implications of mode transitions initiated by the AFCS. The situation occurred during the descent phase of the flight into the Washington National Airport. The aircraft was flying level at 22,000 feet and the VNAV/LNAV pitch/roll mode combination was active. The crew received the following ATC clearance: "cross [the] OJAAY [waypoint] at 10,000 [feet]." The crew acknowledged the ATC constraints and entered them as new target-values into the CDU. During the descent, strong winds from varying directions were encountered between 20,000 and 15,000 feet. To maintain the computed path and target-speed during the descent, the AFCS automatically transitioned between various pitch/thrust sub-mode combinations. These different combinations, which are employed in order to guide the aircraft once it deviated from the path, were not completely clear to the crew.

OFM Representation

The initial mode vector was VNAV-PATH, SPEED, and LNAV for the pitch, thrust, and roll components of the AFCS. The ATC clearance required a modification to the aircraft trajectory (function: *Modify/Monitor Vertical Trajectory;* subfunction: *Modify Trajectory*) (see Figure 1). Once on the descent path, the crew monitored the progress (subfunction: *Monitor Flight Parameters and Modes*; task: *monitor aircraft guidance, monitor mode trajectory, ...*) (see Figure 2).

Discussion

The model highlights the relationship among the three trajectories that must be monitored, understood, and predicted by the crew: (1) the computed path trajectory, (2) the aircraft trajectory, and (3) the mode trajectory. The computed path trajectory describes the intended path over time. The FMC computes a descent path from the cruise altitude to a selected waypoint with an altitude constraint. Once the path is computed (taking into account wind direction and velocity, barometric pressure, etc.) it is not dynamically updated, unless, of course, the crew updates any information and presses "Execute." The aircraft trajectory describes the changes in aircraft state over time. The crew monitors the aircraft parameters (task: *monitor v/s, monitor altitude, monitor speed,...*) to predict this trajectory. In addition the crew monitors the relationship between the aircraft state and the FMC computed path (subtask: *verify aircraft follows path*).

The mode trajectory describes the mode transitions over time. The VNAV mode has two pitch sub-modes (VNAV-PATH, VNAV-SPD) and four thrust sub-modes (THR HOLD, IDLE, SPD, and EPR); various combinations of pitch sub-modes and thrust sub-modes are employed when VNAV is active. In contrast to the computed-path trajectory and aircraft trajectory described in latitude, longitude, altitude, and time space¾mode trajectory is described in a more abstract pitch mode, thrust mode, and time space.

During descent, the VNAV mode automatically triggers pitch/thrust sub-mode combinations in order to guide the aircraft along the computed path (Figure 2, Automatic Mode Engagements). The sub-mode combinations are[1]: (1) VNAV-PATH/IDLE¾indicating the aircraft is on the path and thrust is retarded in order to start the descent, (2) VNAV-PATH/THR-HOLD¾indicating the aircraft is on the path, throttles were initially set at idle, and the throttles are decoupled from the servos, (3) VNAV-PATH/SPD¾indicating that speed was depleting and thrust is now used to maintain the speed target-value, (4) VNAV-SPD/EPR¾indicating that aircraft is behind the path, and thrust is applied to establish a new trajectory in order to intercept the path, (5) VNAV-SPD/THR-HOLD¾indicating the aircraft is still not on the path, a thrust value is set, and the throttles are decoupled from the servos, and (6) VNAV-SPD/IDLE¾indicating an upper speed limit has been reached and the aircraft is leaving the path (and therefore will not cross the waypoint at a constraint altitude!). A "drag required" message, displayed on the CDU, indicates that either speed has reached an upper limit or the aircraft is above the path (the message prompts the pilot to manually extend speed-brakes).

The three trajectories (computed path, mode, and aircraft) have various relationships: the mode and aircraft trajectory are bilaterally coupled, and both are unilaterally coupled to the computed path. The computed path is presented as alphanumeric entries in the CDU. The mode trajectory is predicted by monitoring the text-based mode annunciation and employing prior knowledge of sub-mode behaviors. The aircraft trajectory is predicted by integrating information from cockpit instruments, predictions of mode trajectory, and relationship to the computed path. Several mental transformations (e.g., text-based to spatial) must be performed by the crew in order to predict the aircraft trajectory.

EXAMPLE 3

In this example, the crew was not aware of a certain constraint on data entry; the result was a computed path that was different from intended. The situation occurred during the descent phase of the flight into Washington National Airport. The aircraft was flying level at 33,000 feet, the VNAV/LNAV pitch/roll mode combination was active, and the expected STAR, approach, and runway were already entered. After listening to the ATIS that reported a change in the active runway, the crew entered the new approach (and runway). When the aircraft was about 60 miles west of the JAXSN way-point, the crew received the following ATC clearance: "cross [the] JAXSN [waypoint] at 25,000 [feet]." The captain, who was the pilot-flying, entered the altitude target-value into the CDU. After the captain executed the new entry, the FMC computed a top-of-descent point some 25 miles prior to JAXSN. About 35 miles before JAXSN, the captain engaged the "descend-now" sub-mode of VNAV which commands a shallow descent at a vertical speed of about 1250 feet-per-minute to intercept the computed path. The aircraft started a shallow descent, but did not descend toward meeting the 25,000 feet altitude constraint. When the aircraft was about 15 miles before JAXSN, the crew noticed the problem. The captain immediately engaged the FLCH mode and the aircraft descended to 25,000 feet.

OFM Representation

The initial mode vector was VNAV-PATH, SPEED, and LNAV for the pitch, thrust, and roll components of the AFCS. The new phase was "Descent" and the ATC clearance required a modification to the aircraft trajectory (function: *Modify/Monitor Vertical Trajectory;* subfunction: *Modify Trajectory*) (see Figure 1). The captain entered the ATC constraints into the CDU and then returned to the *Monitor Flight Parameters and Modes* subfunction. After noticing the deviation between the aircraft and path trajectory, the new subfunction was *Modify Trajectory* and the captain engaged the FLCH mode.

Discussion

Although the target-altitude was entered into the CDU, it was not used by the FMC in computing the path; in fact, the altitude target-value entered by the crew was replaced with a schedule altitude of about 28,500 feet. No direct feedback was provided to the crew. The scenario highlights two issues: (1) display of target-values, and (2) sequential constraint on data entry.

The target-values entered by the pilot into the FMC are a critical link between the ATC clearance, the computed path, and the aircraft trajectory. This correspondence has many safety implications. Regardless of which mode is active, a common theme is to maintain, or at least not violate, these target-values. However, target-value information is distributed throughout the cockpit (e.g., FMC¾CDU pages, Autopilot¾MCP, Autothrottles¾TMCP). This leads to instances whereby manipulations of the system (e.g., entering new constraints, engaging different modes) may delete target-values. In these rare, yet possible instances, the AFCS does not explicitly inform the crew that it ignored a target-value.

During the field study the same example was observed three times¾all occurred at the same location and with an identical clearance ("cross JAXSN at 25,000 feet"). One possible reason the AFCS did not compute the intended path may have been related to a sequential constraint on the entry of target-values. One airline provides the following recommended technique in its flight operating manual:

> The B-757 FMC software may, under certain conditions, construct an erroneous vertical path. The resulting arrival may not comply with ATC routing . . . . Use the following sequence whenever you select a STAR to ensure that altitude constraints appear on the LEGS page: (1) STAR, (2) STAR transition (if required), (3) Approach, (4) Approach transition (if required).

CONCLUSIONS

The focus of this paper was to describe and analyze mode transitions in an automated flight control system. Using the operator function model we represented the progression of functions, tasks, and actions needed to comply with the demands of the operating environment. The model highlighted the relationship among the *environmental demands and states* (e.g., ATC clearances, thunderstorms along the flight path), the *functions and tasks* to be accomplished (e.g., Modify Path, Set MCP Altitude Target-Value), and the *physical and cognitive actions* the crew has to undertake. We discussed some of the correspondence between the environmental demands placed on the crew and the AFCS mode behaviors: Example 1 described how the crew shed mismatches between the environmental demands and the VNAV mode by transitioning to FLCH mode, and the resulting tradeoffs in fuel-efficiency and ease of monitoring. Example 2 described the difficulty in understanding the relationship between VNAV sub-mode combinations and the resulting trajectory. Example 3 described a possible mismatch between the crew's goal of complying with the ATC clearance and the non-intuitive action sequences necessary to achieve it.

This exercise also allowed us to identify some of the limitations and capabilities of this modeling approach for describing mode transitions. One limitation of the OFM, as well as most human-machine models, is that it does not explicitly model the behavior of the hardware/software system. However, modeling this behavior is critical for describing operator interactions with a control system that initiates automatic mode transitions. Another limitation is the difficulty in formally describing interactions between actions (i.e., nodes in the model), specifically when these nodes are depicted on different branches in the tree-like decomposition. This is particularly important if two or more processes are coupled (e.g., pitch, thrust, and speed in an aircraft; pressure and heat in a boiler). Nevertheless, one marked advantage of such modeling effort is the capability to *formally* describe aspects of human-automation interaction. Another advantage is that such models are *systematic*¾in building the model, the modeler can be complete. Although beyond the focus of this paper, a formal model can also be represented in an analytic or computational format. Both formats allow the modeler to test the model using mathematical proofs and/or conducting simulations.

We therefore suggest here the utility of task-analysis models for understanding human-automation interaction. Such modeling efforts can aid the design and evaluation process by (1) *describing* this interaction in a language that can be reviewed and verified jointly by pilots, engineers, and human-factor specialists, (2) *providing a benchmark* in the iterative design process, and (3) *highlighting* to the experienced modeler the potential for human-automation problems.

REFERENCES

Aviation Week and Space Technology. (1995). Automated cockpits: who's in charge? Part 1 and 2. *142*(5-6).

Casner, S. M. (1995). Understanding the determinants of problem-solving behavior in a complex environment. *Human Factors, 36*(4), 580-598.

Degani, A., Shafto, M., and Kirlik, A. (in press). Mode usage in automated cockpits: Some initial observations. In T. B. Sheridan (Ed.), *Proceeding of the International Federation of Automatic Control: Man-Machine Systems (IFAC-MMS) Conference*. Boston, MA: IFAC.

Degani, A., and Wiener, E. L. (1994). *On the design of flight-deck procedures* (NASA Contractor Report 177642). Moffett Field, CA: NASA Ames Research Center.

Eldredge, D., Dodd, R. D., and Mangold, S. J. (1991). *A review and discussion of flight management system incidents reported to the aviation safety reporting system.* Cambridge, MA: Volpe National Transportation Systems Center.

Lambergts, A. A. (1983). *Operational aspects of integrated vertical flight path and speed control system* (Society of Automotive Engineers [SAE] technical paper 831420). Warrendale, PA: Society of Automotive Engineers.

Mitchell, C. M. (1987). GT-MSOCC: A domain for research on human-computer interaction and decision aiding in supervisory control systems. *IEEE Transactions on Systems, Man and Cybernetics, SMC-17*(4), 553-572.

Sarter, N. B., and Woods, D. D. (1994). Pilot interaction with cockpit automation II: An experimental study of pilot's mental model and awareness of the flight management and guidance system. *International Journal of Aviation Psychology, 4*(1),1-28.

ENDNOTES

[1] This list is not exhaustive and the sub-mode combinations may depend on a particular software.

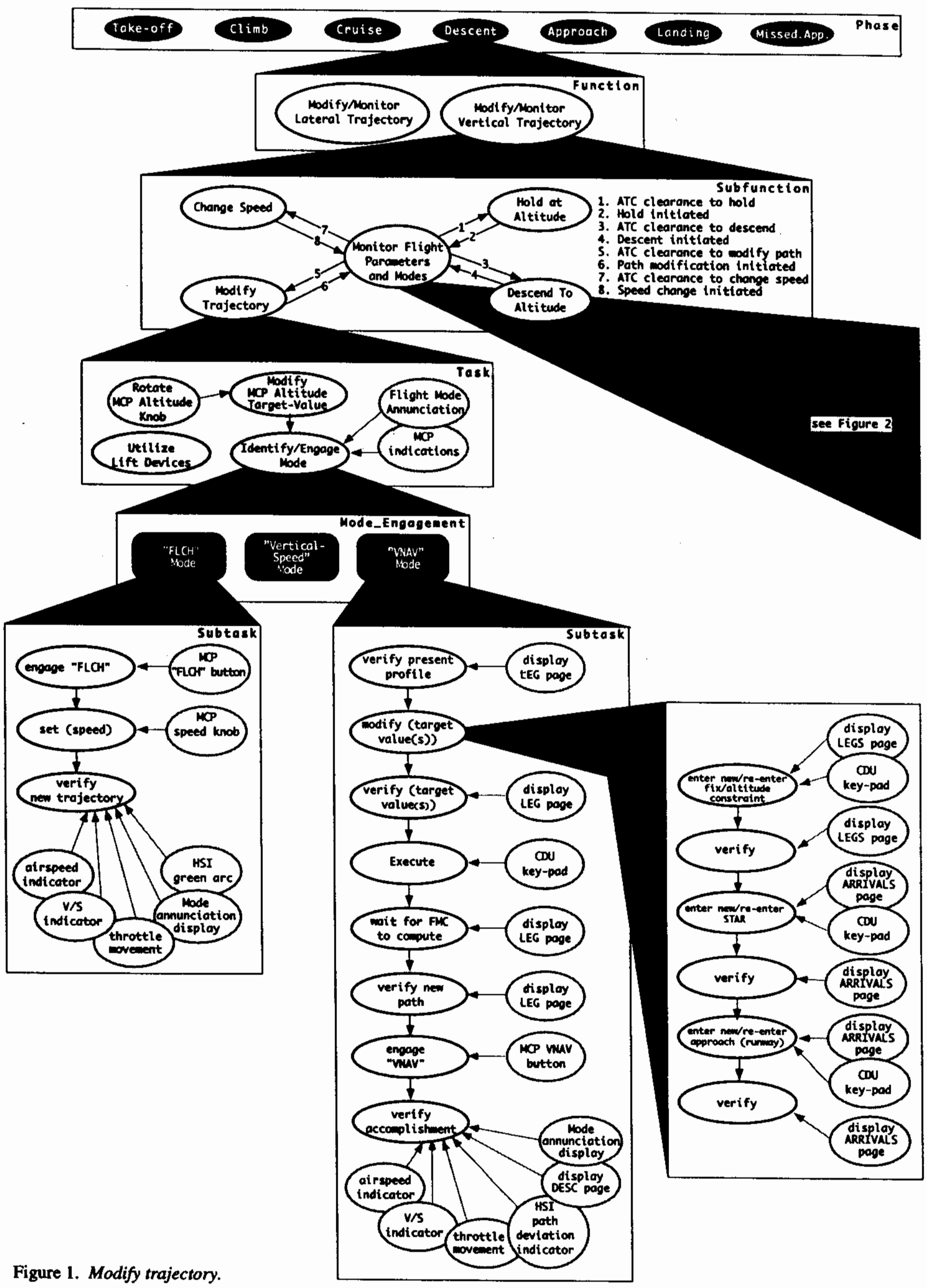

Figure 1. *Modify trajectory.*

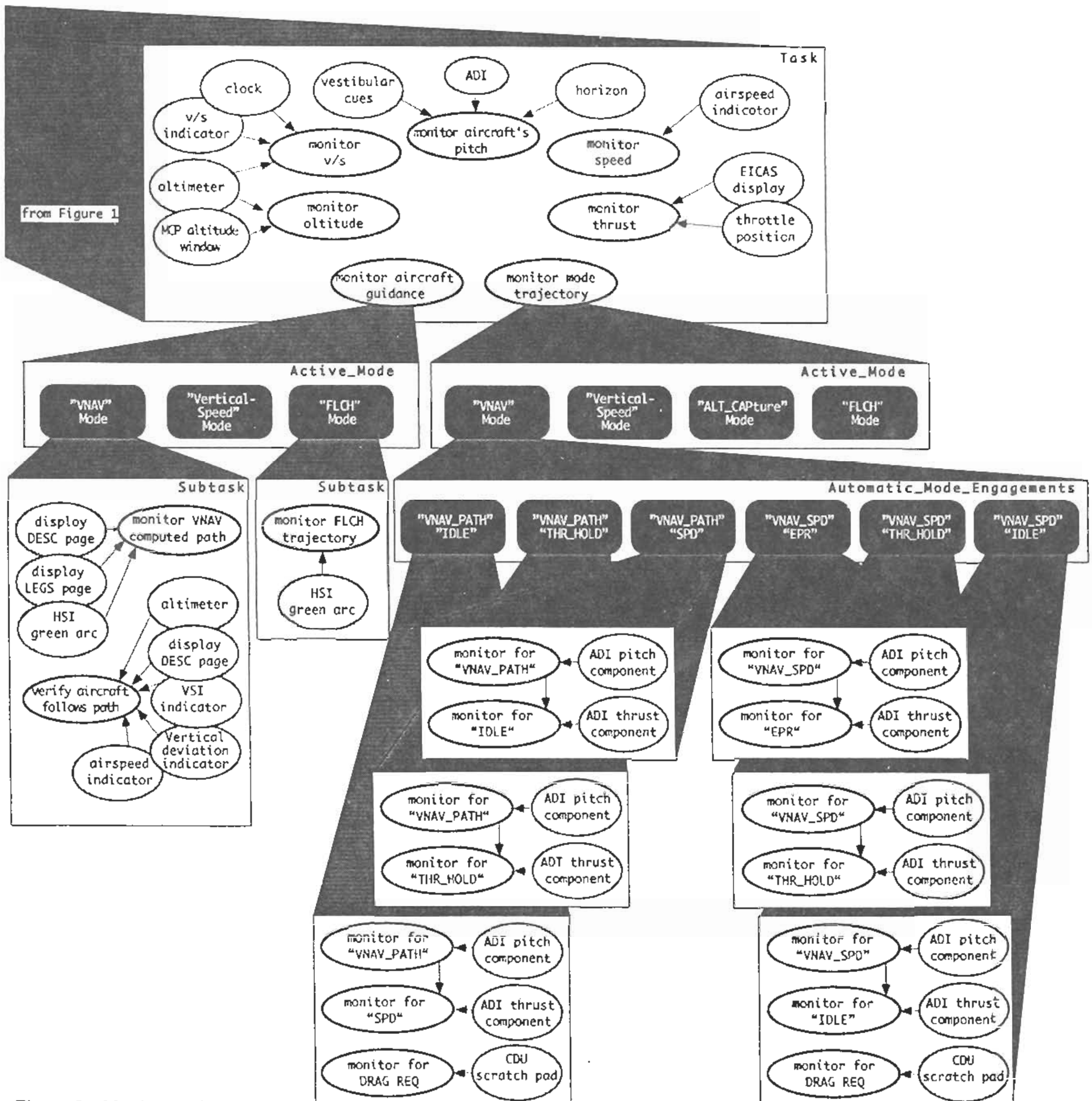

Figure 2. *Monitor trajectory.*